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Cost performance and bullwhip effect in a hybrid manufacturing and remanufacturing system with different control policies

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In recent years, remanufacturing has emerged as an important research area. This requires developing methods and models in order to aid companies in systematically evaluating current as well as projected remanufacturing systems. This paper addresses the inventory control problem in a hybrid inventory system with manufacturing and remanufacturing options. In this study, by changing the definition of inventory position of the serviceable stock, we introduce a shift PULL inventory control policy, which is compared with PULL, DUAL, and Separate PULL control policies studied previously in the literature. Besides evaluating the economic consequences with different control policies, we also study system dynamic behaviour such as the bullwhip effect, in order to understand the advantages and disadvantages of different policies. After the experiments, we propose several management guidelines for such a hybrid inventory system. The major findings are: (1) separate PULL and DUAL can be good alternatives when the manufacturing lead time is significantly longer than the remanufacturing lead time; (2) shifted PULL exhibits a good performance when the two lead times differ slightly. Owing to the complexity in solving the optimization problem, a simulation approach is used.

Keywords: Remanufacturing; Reverse logistics; Closed-loop supply chain; Hybrid inventory systems; Bullwhip effect; Simulation

1. Introduction

Remanufacturing represents an important form of reuse and focuses on value-added recovery. It has been introduced in many different fields such as automobiles, telecommunication, electrical equipment, machinery, etc. In addition to economic profitability, there is legislation that assigns the producers the responsibility for used products, for instance Directive 2002/96/EC related to Waste Electrical and Electronic Equipment and Directive 2002/525/EC related to End of Life Vehicles. Remanufacturing has become an important industrial sector in achieving the goal of sustainable development.

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In this paper, we study an inventory system with manufacturing and remanufacturing options. The inventory control policies in this case are often extended from the traditional inventory control models such as (s, Q) and (s, S). The optimal control policy in general is not yet known, except for the case with equal lead times (Kiesmüller 2003). The most common policies in literature are PUSH and PULL, introduced by van der Laan and Salomon (1997) and then studied by van der Laan *et al.* (1999), Inderfurth and van der Laan (2001), Kiesmüller (2002, 2003), Teunter *et al.* (2004), among others. These two policies are also widely used in practice.

When the above two policies are implemented, an interesting finding is a so-called lead-time paradox, i.e. a short lead time does not necessarily enhance the system performance, especially when the manufacturing and remanufacturing lead times differ considerably (van der Laan *et al.* 1999, Inderfurth and van der Laan 2001, Kiesmüller 2003). This is interpreted as information distortion in the order-releasing process. In the standard PUSH and PULL policies, manufacturing orders are triggered by the serviceable inventory position, which is defined as on-hand inventory minus backlogs plus outstanding manufacturing and remanufacturing orders. When the lead times differ, this inventory position prevents the possibility of using a fast production model and does not take into account the potential of overstocking remanufactured items. In order to improve the system performance, Inderfurth and van der Laan (2001) modify the policies by postponing remanufacturing orders and reducing the serviceable inventory level, whereas Kiesmüller (2003) and Teunter *et al.* (2004) examine redefining the inventory position so that better information will be used in making order-releasing decisions.

Instead of modifying PUSH and PULL policies, Tang and Grubbström (2005) investigate the benefit of applying a DUAL sourcing policy in the manufacturing and remanufacturing system, i.e. an order is split between two production options. Such an ordering policy reduces inventory holding costs as well as backorder costs when the two lead times are stochastic. In the above study, demand and return rates are considered as deterministic. A preliminary study (Zanoni *et al.* 2004) shows that DUAL outperforms PUSH and PULL when lead times are significantly different. Thus, the DUAL policy can complement PUSH and PULL policies in the manufacturing and remanufacturing system.

This background provides the motivation for the current study. We investigate which control policies should be implemented in order to improve the performance in a manufacturing and remanufacturing system with stochastic lead times, stochastic demand and return. Following the same principle as in Kiesmüller (2003), we develop new inventory position definitions for manufacturing and remanufacturing decisions, so that only important inventory and order-releasing information is aggregated. Since PULL policy often outperforms PUSH policy (van der Laan *et al.* 1999), in this study we exclude the latter.

The impact of system parameters on system performance is investigated to understand which policy should be implemented and under what circumstances. In addition to costs, we also consider the bullwhip effect as a performance measure, since it is an important indicator of how a sub-production system copes with the entire supply chain. Since the system with multiple stochastic elements is difficult, if not impossible, to model and solve analytically (Tang and Grubbström 2005), we use a simulation approach in this study.

The remainder of this paper is organized as follows. In section 2, we first present the hybrid production system and the standard inventory replenishment policies. Then, we outline the new definitions of the inventory positions and discuss the performance measurement. In section 3, the simulation method is described, including the model and parameter settings. In section 4, the results are presented and discussed. Finally, in section 5, we make concluding remarks and provide ideas for future studies.

2. The problem

2.1 *System description*

We study a hybrid manufacturing and remanufacturing system. The material flows are illustrated in figure 1. Some items come back to the recoverable inventory after their use by the customer. Customer demand is met by the serviceable stock, which can be replenished by either manufacturing or remanufacturing. These two processes supply the same product, assuming that the remanufactured products are 'as good as new', but the lead times often differ. In this study, we further assume that the lead times, demand, and return processes are stochastic. A disposal option for return items is not included. As shown in Teunter and Vlachos (2002), such an option generally does not lead to a significant cost reduction. In the system described above, one inventory management issue is to define the inventory control policy at the serviceable stock site: when to order, where to order, and how many to order.

2.2 *PULL and DUAL policies*

According to van der Laan *et al.* (1999), in a PULL system (s_m, Q_m, s_r, S_r) remanufacturing starts whenever the inventory position of serviceable inventory drops to s_r, and there is sufficient recoverable inventory to increase the inventory position to S_r. Manufacturing takes place when the inventory position of serviceable stock drops to s_m (figure 2). The batch size for manufacturing is always Q_m. Usually, the reorder point for manufacturing is no greater than that for remanufacturing $s_m \leq s_r$ (figure 2). In this case, the recoverable item is pulled into the process when demand occurs, so the policy is named PULL.

The DUAL (s, Q) policy extends the traditional dual sourcing policy (for details, see Tang and Grubbström 2005). When the inventory position of the serviceable
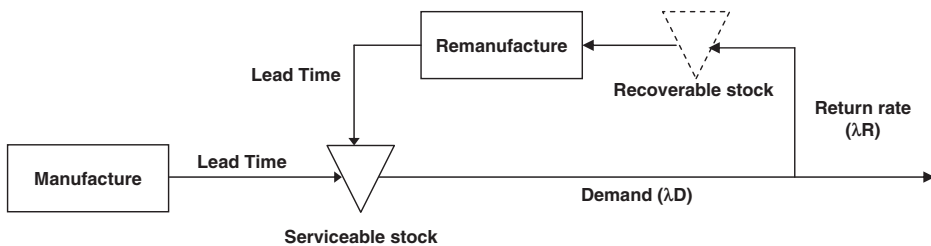

Figure 1. The material flow in a simple manufacturing/remanufacturing system.
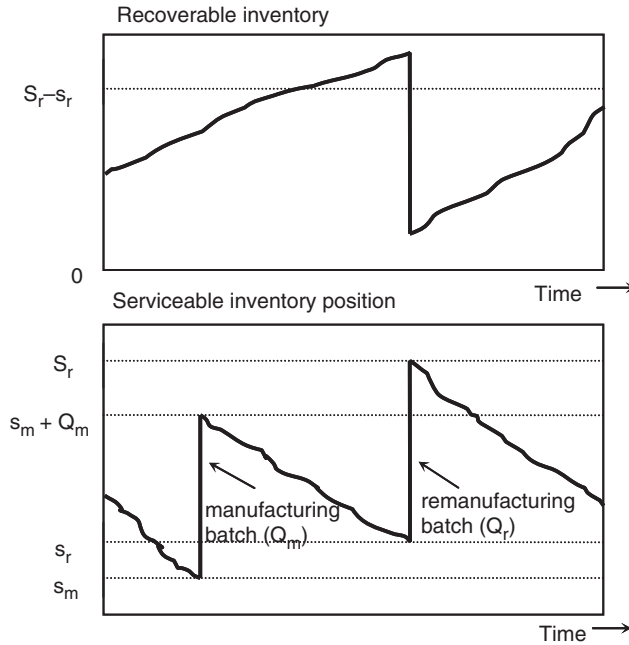
Recoverable inventory

Figure 2.   Inventory profile with a PULL policy.

stock drops to or below the reorder point s, a replenishment order is triggered. This order is split into manufacturing and remanufacturing orders. If the recoverable inventory Q_r is less than Q, Q_r amount is ordered from remanufacturing process and the rest $(Q - Q_r)$ from manufacturing. Otherwise, all Q items are ordered from remanufacturing. The inventory profile in a DUAL system is illustrated in figure 3.

The serviceable inventory position is defined in the same way for the PULL and DUAL policies. It includes the on-hand serviceable inventory minus backorders plus all outstanding manufacturing and remanufacturing orders.

2.3 *Two modified policies*

In the above-mentioned inventory control policies, manufacturing and remanufacturing orders are triggered by examining the inventory position. In the following, the serviceable net-stock (stock-on-hand minus backorders) at time t is denoted with $I_s(t)$. Furthermore, at decision time point t, we have $m(t_1, t_2)$ as the outstanding manufactured orders which are released in the time interval $[t_1, t_2]$, with $t_1 < t_2 \leq t$. Correspondingly, we have outstanding remanufactured orders $r(t_1, t_2)$.

By using this notation, the commonly used inventory position in the literature, defined as the stock-on-hand in the serviceable inventory minus backorders plus all outstanding remanufacturing and production orders released before t, can be written as:

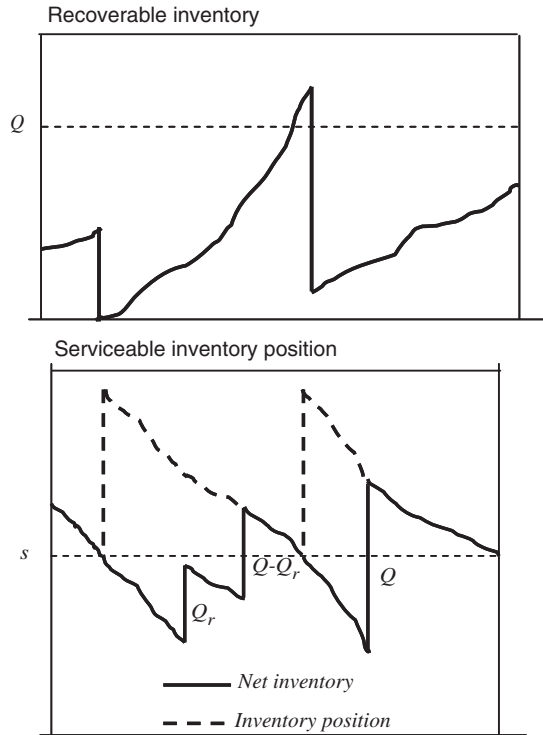$$X(t) = I_S(t) + m(t - T_m, t) + r(t - T_r, t), \tag{1}$$

Recoverable inventory

Serviceable inventory position

Figure 3.   Inventory profile with a DUAL policy.

where T_m and T_r are, respectively, the expected manufacturing and remanufacturing lead times in stochastic case.

2.3.1 Shifted PULL policy.   Now, in order to capture the most important inventory and ordering information, we introduce a modified inventory position, considering two additional decision variables which can be optimized.

To this end, for the PULL policy, we aggregate outstanding orders in two modified inventory positions, which are used for the manufacturing and remanufacturing decisions, respectively.

At decision time point t, we calculate remanufacturing inventory position as serviceable net-stock, all manufacturing outstanding orders released during time interval $[t - T_m, t - L_r]$ and all remanufacturing outstanding orders released during time interval $[t - T_r, t - L_r]$. This leads to the following definition

$$X_r(t) = I_s(t) + m(t - T_m, t - (T_m - L_r)) + r(t - T_r, t - (T_r - L_r)). \qquad (2)$$

As illustrated in figure 4, only the outstanding orders M_1, M_2, and R_1 will be included in the inventory position. When the manufacturing and remanufacturing lead times are deterministic, these outstanding orders should arrive in the time interval $[t, t + L_r]$. Here, L_r is a decision variable in our modified replenishment policy and can be optimized via simulation. As this inventory position is lower than
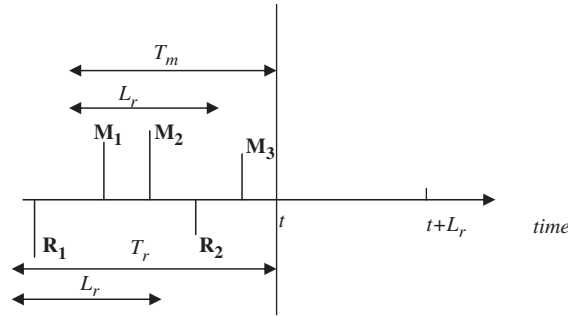
Figure 4.   Time scale in defining the new inventory position for the shifted PULL policy.

that defined in equation (1), we retain the chance to trigger a fast production model and therefore reduce the backorders. In a deterministic lead-time case, L_r should not be larger than $\min(T_m, T_r)$, because any time beyond $t + \min(T_m, T_r)$ need not be protected due to the availability of the fast production model. Since the protection time interval $[t, t + L_r]$ is small, we can also reduce the safety stock level, the reorder point, and then the inventory holding cost.

In the same way, the inventory position for the manufacturing decision is written as

$$X_m(t) = I_s(t) + m(t - T_m, t - (T_m - L_m)) + r(t - T_r, t - (T_r - L_m)). \qquad (3)$$

Since lead times are stochastic in this study, we cannot discern which actual lead time is larger. Therefore, in the above definitions, we do not discriminate between the cases with a large remanufacturing lead time or a large manufacturing lead time. This is also one major difference between our model and the one in Kiesmüller (2003).

2.3.2 Separate PULL policy.   With the aim of comparing the performances of the proposed Shifted PULL policy, we also use a modified PULL policy proposed by Teunter *et al.* (2004), named Separate PULL. The main objective of this policy is to separate as much as possible manufacturing decisions and remanufacturing decisions. The policy is introduced for the special case in which the remanufacturing process is faster than the manufacturing process. In this context, the underlying logic is that long-term manufacturing decisions should control the total stock in the system (serviceable inventory position plus remanufacturables), while short-term remanufacturing decisions should control the serviceable stock on hand plus orders with remaining lead time at most T_r. Thus, the two following inventory positions are used for manufacturing and remanufacturing decisions:

$$X_m(t) = I_s(t) + I_r(t) + m(t - T_m, t) + r(t - T_r, t) \qquad (4)$$

$$X_r(t) = I_s(t) + m(t - T_m, t - (T_m - T_r)) + r(t - T_r, t). \qquad (5)$$

The main conclusion of Teunter *et al.* (2004) is that for hybrid inventory systems with slow manufacturing and fast remanufacturing, the Separate PULL strategy performs much better than standard PUSH and PULL.

2.4 *System performances*

2.4.1 System costs. For both policies described above, we need to evaluate the system performance. The total cost during the planning horizon T is

$$TC = b \cdot I_s^-(T) + h_s \cdot I_s^+(T) + h_r \cdot I_r(T) + K_m \cdot M(T) + K_r \cdot R(T), \qquad (6)$$

where b is the backorder cost when demand occurs but is not satisfied, h_s is the holding cost for the serviceable inventory, h_r is the holding cost for the recoverable inventory, K_m is the setup cost when a manufacturing order is released, and K_r is the setup cost when a remanufacturing order is released. $I_s^-(T)$, $I_s^+(T)$, and $I_r(T)$ are the backorder, serviceable inventory, and recoverable inventory during planning horizon T, respectively. $M(T)$ and $R(T)$ are the total number of manufacturing and remanufacturing setups.

The marginal costs for manufacturing and remanufacturing are not taken into account. From a long run viewpoint, these two costs are constant, since the system has a stable return rate, and there is no disposal. One should be aware that we need to take extra care when evaluating the inventory-holding-cost rate. Traditionally, we consider inventory holding cost as a capital tied-up due to the cost for obtaining the products. Since, in general, the marginal manufacturing and remanufacturing costs are different, it becomes more complicated to evaluate how much capital has been tied up in a serviceable product (Teunter 2001, Tang *et al.* 2004).

2.4.2 Bullwhip effect. Besides the total cost, we also evaluate an external performance measure, the bullwhip effect. Since its first theorization (e.g. Forrester 1961), the bullwhip effect has received much attention as it creates a business environment that can significantly add unnecessary costs (Metters 1997). To indicate the system dynamics, some authors (e.g. Chen *et al.* 2000, Disney *et al.* 2004) have recently been using the ratio of the long-term variance of orders (OR) over the long-term variance of demand (D) as a measure of the bullwhip effect

$$\text{Bullwhip index} = \frac{\sigma_{OR}^2}{\sigma_D^2}. \qquad (7)$$

This metric can be applied to a single echelon in a supply or across many echelons in the supply chain (Dejonckheere *et al.* 2004). With a small bullwhip index value, we have a smooth production system (Disney *et al.* 2004).

Although this study does not consider capacity constraints in the manufacturing and remanufacturing system, it is important for examining the bullwhip effect. It determines the extent to which our production process has to re-evaluate resource positioning from one time period to the next and the level at which capacity has to be held to satisfy requirements. In addition, when a manufacturing order is triggered, it often leads to additional material requirements, and the information needs to be transferred to the upstream members in a supply chain. Investigation of the bullwhip

and variance ratio effects in a closed-loop supply chain can also be found in Tang and Naim (2004), Zhou and Disney (2006), and Zhou *et al.* (2006).

The bullwhip effect index which is taken into account in our study refers to the manufacturing and remanufacturing processes. The bullwhip effect is slightly modified with respect to that defined above, due to the presence of the return stream

$$\text{Bullwhip} = \frac{\sigma_{\text{OR}}^2/\mu_{\text{OR}}}{\sigma_{\text{D}}^2/\mu_{\text{D}}}, \tag{8}$$

where σ^2 is the variance, and μ is the mean. The mean values are used to normalize the index. The random external demand is the input to the system, and either the manufacturing order or remanufacturing order is considered as OR. This leads to the following two bullwhip indexes:

$$\text{Bullwhip}_{\text{Manufacturing}} = \frac{\sigma_{\text{Manufacturing orders}}^2/\mu_{\text{Manufacturing orders}}}{\sigma_{\text{D}}^2/\mu_{\text{D}}} \tag{9}$$

$$\text{Bullwhip}_{\text{Remanufacturing}} = \frac{\sigma_{\text{Remanufacturing orders}}^2/\mu_{\text{Remanufacturing orders}}}{\sigma_{\text{D}}^2/\mu_{\text{D}}}. \tag{10}$$

3. Simulation model

The simulation model is coded in Arena® 8.01 (by Rockwell Software Inc.) simulation software. Moreover, we adopt the optimization module OptQuest® 7.0 (further details can be found in Kelton *et al.* 2004) in Arena® to determine the optimal control parameters for the different policies investigated. A range of different scenarios are considered by defining a base case and then varying key parameters. Each scenario is simulated for $T = 10\,000$ and replicated 10 times. The number of replications is sufficient to obtain a small variance in the simulation results, enabling all the simulations to be included in a 95% confidence interval. The base-case values are listed in table 1. These costs are based on a price of €1000 per finished product. Marginal costs are €200 for each serviceable product and €100 for recoverable product. Inventory holding costs are $h_{\text{s}} = 200 \times 0.001 = 0.2$ and $h_{\text{r}} = (200 - 100) \times 0.001 = 0.1$. Here, we follow the research results in Teunter (2001) to calculate h_{r} based on the net profit of remanufacturing.

The uncertainty in our system comes from four different sources: demand process, return process, manufacturing and remanufacturing lead times. In the simulation model, the demand and return in each period follow a Poisson process. In the base case the return rate ratio r ($r = \lambda_{\text{R}}/\lambda_{\text{D}}$) is 0.8. The stochastic lead times for manufacturing and remanufacturing one complete batch obey a gamma distribution.

4. Results and analysis

In this section, the optimal decisions for the four control policies are obtained and compared. System performances, in terms of cost and the bullwhip effect, are investigated by changing two important parameters. First, we vary the mean value of

Table 1. Parameters in a base case.

Parameter (unit of measure)	Symbol	Value
Demand rate (units/period)	λ_D	5
Return rate (units/period)	λ_R	4
Mean value of remanufacturing lead time (period)	T_r	4
Variance of remanufacturing lead time (period^2)	$\sigma^2_{T_r}$	1
Mean value of manufacturing lead time (period)	T_m	8
Variance of manufacturing lead time (period^2)	$\sigma^2_{T_m}$	1
Backorder cost (€/period/unit)	b	10
Remanufacturing cost (€/batch)	K_r	2
Manufacturing cost (€/batch)	K_m	5
Holding cost of serviceable inventory (€/period/unit)	h_s	0.2
Holding cost of recoverable inventory (€/period/unit)	h_r	0.1

manufacturing lead time and keep the mean value of remanufacturing lead time as a constant. The variances of the two lead times remain unchanged. We use five levels of mean lead-time ratio $T_m/T_r = 0.5, 1, 1.5, 2, 3$. Second, we investigate return-rate levels from low to high, $r = 0.2, 0.4, 0.6, 0.8$. The simulation results are illustrated in figures 5 and 6. Optimal control variables are illustrated in table 2.

4.1 *Observation 1*

Shifted PULL always generates a better result than the PULL policy. With a shifted PULL policy, the control variables L_m and L_r have been optimized. Therefore, only 'optimal' information (inventory position) has been taken into account in order-releasing decisions. This yields better results than PULL, which is the special case whereby $L_m = \infty$ and $L_r = \infty$. The difference between the two policies is small with a high T_m/T_r ratio (figure 5). This is interpreted as being due to relatively large optimal values of L_m and L_r, and to the fact that most of the outstanding orders have been included in determining the inventory position.

4.2 *Observation 2*

Separate PULL is the best policy when the T_m/T_r ratio is higher than 1.5. This result is not surprising, as this policy is adapted for a fast remanufacturing system, as illustrated in Teunter *et al.* (2004). Our study confirms the advantages of a separate PULL policy.

4.3 *Observation 3*

The performance of the DUAL policy depends on both T_m/T_r and the return rate level. From figure 5, we can see that this policy has a similar behaviour to the separate PULL policy when the T_m/T_r ratio is high. With a DUAL policy, when the inventory position drops below the reorder point, manufacturing and remanufacturing orders will be released simultaneously. When the manufacturing time is significantly longer than the remanufacturing time, the manufacturing order
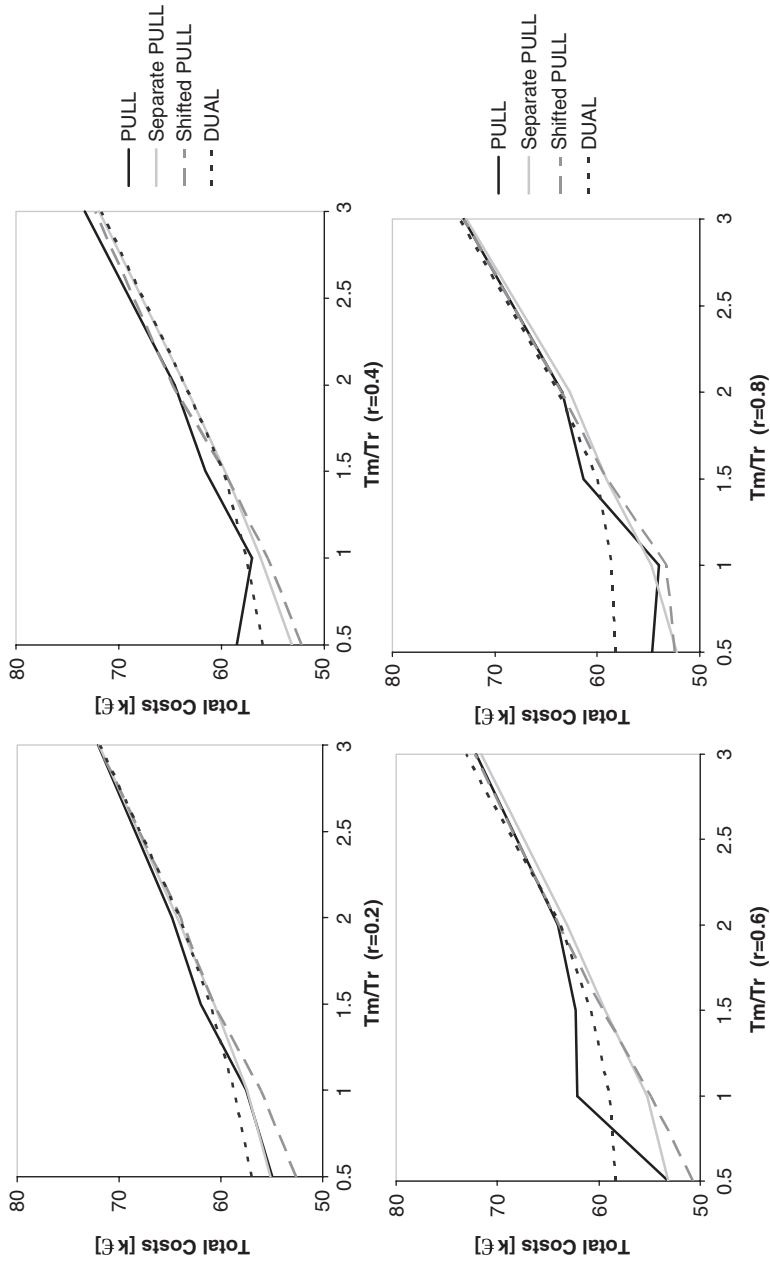
Figure 5. Total costs as a function of mean manufacturing and remanufacturing lead time ratio for four return rate levels.
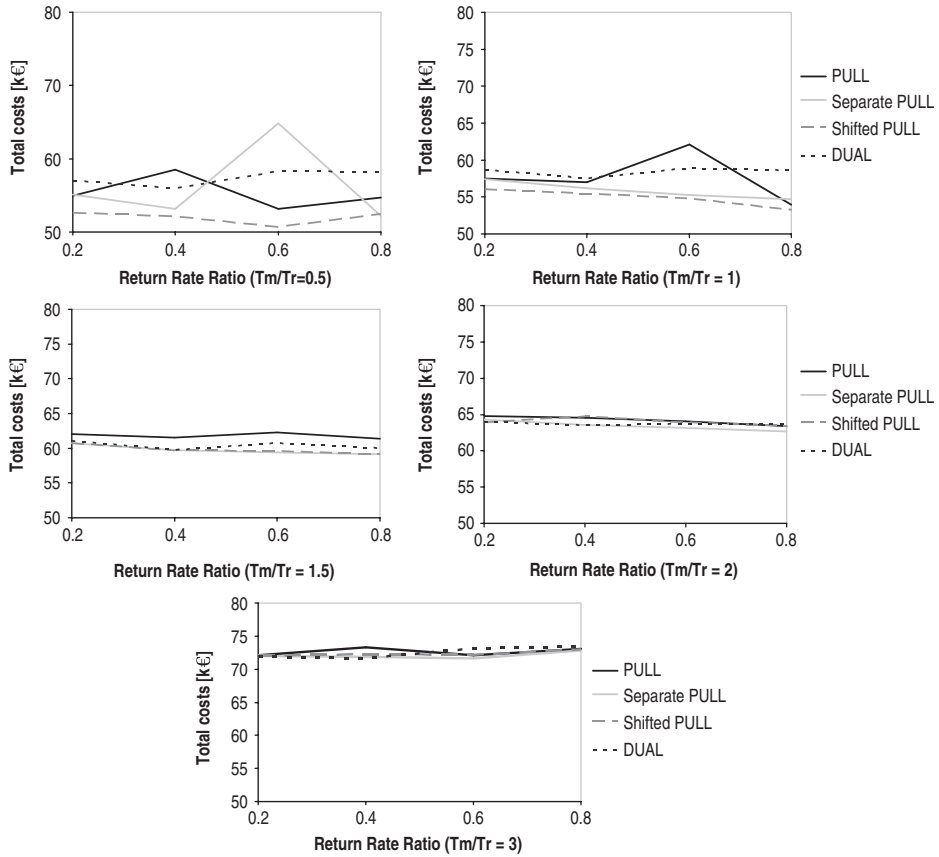
Figure 6. Total costs as a function of return rate for five levels of lead time ratio.

will arrive with a time lag, and so the inventory holding cost can be reduced. On the other hand, the early arrival of the remanufacturing batch reduces the chance of having backorders. The average order sizes of manufacturing and remanufacturing are determined by the return ratio. Ideally, during the time lag between the manufacturing and remanufacturing orders, the first order to arrive should be consumed, and the inventory level should drop back again to an appropriate 'safety stock' level. In this case, both the inventory and backorder reduction effect will be improved. Therefore, the return ratio should play an important role in determining the performance of the DUAL policy.

4.4 *Observation 4*

The shifted PULL policy is the best policy if $T_m/T_r < 1.5$. Separate PULL is not suitable for fast manufacturing, and the DUAL policy does not perform well when the two lead times are close together. Thus, shifted PULL provides the best choice (figure 6).

Table 2. Values of optimal decision variables for four policies with different scenarios.

|		T_m/T_r				
		0.5	1	1.5	2	3
r = 0.2						
Dual (Q, s_r)		17, 16	21, 24	22, 33	23, 42	21, 60
Pull (Q_m, Q_r, s_m, s_r)		15, 5, 17, 35	15, 6, 25, 29	21, 5, 34, 47	18, 6, 44, 55	20, 6, 63, 78
Separate Pull (Q_m, Q_r, s_m, s_r)		16, 5, 19, 26	18, 5, 27, 27	14, 5, 37, 37	20, 6, 45, 45	25, 5, 64, 68
Shifted Pull (Q_m, Q_r, s_m, s_r, L_m, L_r)		16, 5, 15, 26, 3, 4	17, 5, 24, 30, 5, 5	14, 5, 34, 34, 6, 10	18, 6, 44, 56, 9, 7	20, 6, 63, 78, 14, 6
r = 0.4						
Dual (Q, s_r)		18, 16	21, 22	22, 29	24, 37	22, 51
Pull (Q_m, Q_r, s_m, s_r)		12, 10, 22, 24	14, 8, 26, 32	13, 8, 35, 35	16, 7, 40, 50	21, 8, 53, 69
Separate Pull (Q_m, Q_r, s_m, s_r)		15, 7, 21, 31	15, 7, 28, 28	15, 6, 35, 35	16, 8, 45, 45	14, 7, 58, 62
Shifted Pull (Q_m, Q_r, s_m, s_r, L_m, L_r)		13, 6, 17, 24, 3, 5	15, 6, 24, 29, 5, 5	15, 7, 32, 40, 7, 15	18, 6, 38, 65, 9, 8	16, 8, 55, 66, 14, 18
r = 0.6						
Dual (Q, s_r)		16, 20	17, 24	21, 27	24, 31	22, 43
Pull (Q_m, Q_r, s_m, s_r)		13, 10, 20, 27	14, 14, 28, 58	8, 9, 31, 31	13, 7, 36, 46	15, 7, 47, 57
Separate Pull (Q_m, Q_r, s_m, s_r)		15, 23, 36, 36	13, 7, 28, 50	12, 8, 35, 35	13, 8, 40, 40	19, 10, 51, 51
Shifted Pull (Q_m, Q_r, s_m, s_r, L_m, L_r)		15, 8, 16, 27, 3, 4	13, 7, 24, 58, 5, 6	11, 8, 30, 31, 6, 9	13, 7, 36, 44, 10, 6	15, 7, 47, 57, 16, 10
r = 0.8						
Dual (Q, s_r)		12, 22	13, 25	15, 28	14, 31	16, 39
Pull (Q_m, Q_r, s_m, s_r)		15, 8, 15, 37	14, 8, 23, 28	15, 10, 30, 33	12, 8, 33, 36	9, 8, 40, 46
Separate Pull (Q_m, Q_r, s_m, s_r)		12, 8, 24, 28	10, 8, 28, 28	9, 8, 33, 35	13, 8, 35, 35	18, 8, 41, 41
Shifted Pull (Q_m, Q_r, s_m, s_r, L_m, L_r)		14, 7, 18, 37, 3, 5	10, 8, 23, 28, 5, 5	12, 8, 28, 31, 6, 7	12, 8, 33, 36, 12, 9	9, 8, 40, 46, 13, 7
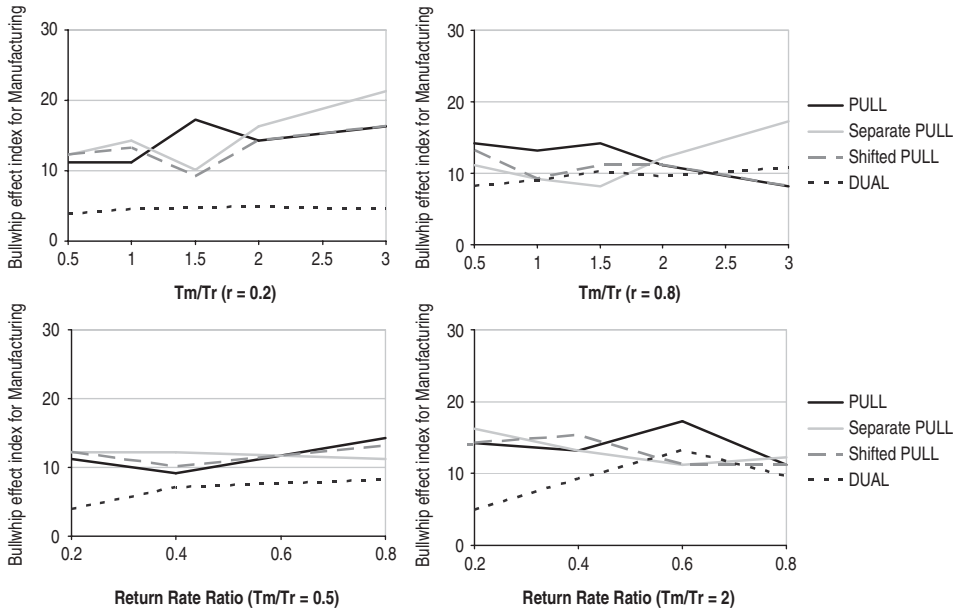
Figure 7. Manufacturing bullwhip effect index for the different policies for four scenarios.

4.5 *Observation 5*

The optimal values for the decision variables L_m and L_r in shifted PULL are affected more by the lead time ratio than by the return rate. This observation follows mainly from the results in table 2. The principle of shifted PULL is to use appropriate inventory position information (by adjusting the values of L_m and L_r) in order releasing. Since the time period which needs to be protected (from backorders) changes along with the lead time, the optimal reorder point as well as L_m and L_r should change with the lead time. We also note that with equal lead times, the optimal values of L_m and L_r are equal in many cases. The second part of the experiment focuses on the bullwhip effect, in both manufacturing and remanufacturing processes. The bullwhip effect indexes in the two processes are reported in figures 7 and 8.

4.6 *Observation 6*

The DUAL policy usually yields a better result in terms of manufacturing bullwhip. The results shown in figures 7 reveal that the performance of the DUAL policy is usually better than that of other policies in terms of the manufacturing bullwhip effect. In particular, the DUAL policy significantly outperforms the other policies when the return rate is low. This derives from the fact that in the DUAL policy, unlike the other policies, manufacturing is often needed when an order is released, except where the recoverable inventory Q_r is larger than Q. However, the situation $Q_r > Q$ occurs only when the return rate is high. This implies a more regular release of manufacturing orders.
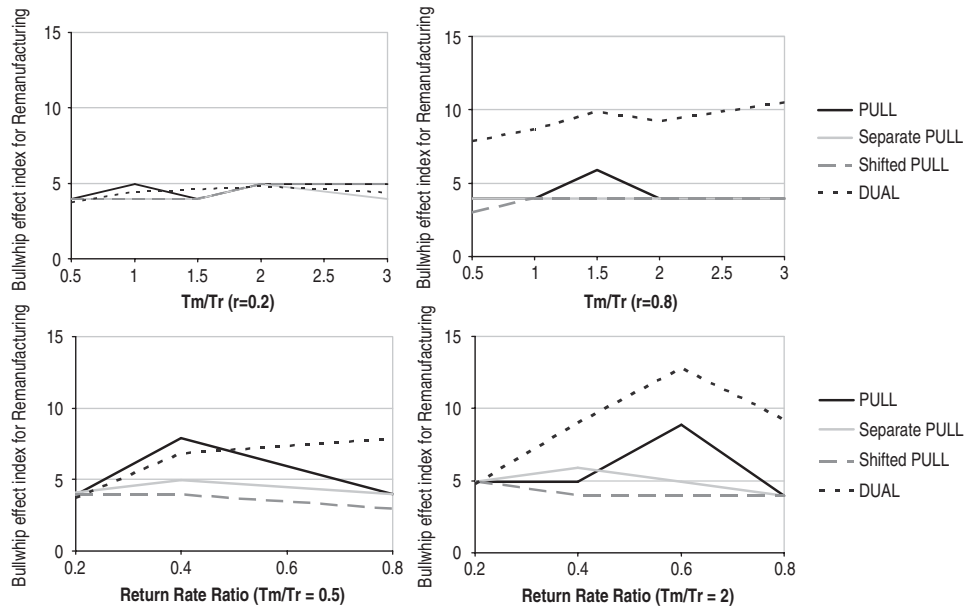
Figure 8.   Remanufacturing bullwhip effect index for the different policies for four scenarios.

4.7 *Observation 7*

The shifted PULL policy always generates a better result in terms of remanufacturing bullwhip. The results shown in figure 8 reveal that the performance of the shifted PULL policy is always better than other policies in terms of the remanufacturing bullwhip effect. Shifted PULL shows a relative insensitivity, confirming its outstanding performance in terms of lower remanufacturing bullwhip in the whole set of experiments carried out. With a low return rate (i.e. equal to 0.2) different policies exhibit similar values of remanufacturing bullwhip, whereas with a high return rate (i.e. equal to 0.8), the DUAL policy performs worse than other policies. Consistent benefits, in terms of remanufacturing bullwhip, can be observed for intermediate levels of return rate, i.e. in our experiments equal to 0.4 and 0.6, for each level of lead-time ratio. This may be explained as the behaviour of the Shifted PULL policy which releases remanufacturing orders according to a shifted lead time, in this way intervals between remanufacturing activities has a reduced level of variability in comparison with the other two PULL policies (i.e. standard and separated).

5. **Conclusions**

In this paper, we have compared different inventory control policies in a hybrid manufacturing/remanufacturing system where demand, return rate, and lead times are stochastic. Standard PULL and separated PULL policies are used as benchmarks to investigate the possible advantages of DUAL policy and the newly proposed

shifted PULL policy. In the latter, the manufacturing and remanufacturing decisions are based on two different definitions of the inventory position, which are developed from Kiesmüller (2003).

Through simulation experiments, the separate PULL policy has been reinvestigated. By comparing the cost performance alone, it has been confirmed that this policy performs very well with respect to the total cost when the remanufacturing lead time is shorter than the manufacturing lead time (high $T_\mathrm{m}/T_\mathrm{r}$ ratio), as claimed by Teunter *et al.* (2004). This policy therefore can be used as a benchmark in a fast remanufacturing system when evaluating other new policies. When the two lead times T_m and T_r differ slightly, shifted PULL will be a good choice. The analysis of DUAL policy is more complicated. In order to obtain a good cost performance with DUAL policy, a large lead-time difference (either a high $T_\mathrm{m}/T_\mathrm{r}$ ratio or a high $T_\mathrm{r}/T_\mathrm{m}$ ratio) is required, and in addition the return ratio should cope with the time difference.

Moreover, we calculate the bullwhip effect for different scenarios after the cost has been minimized, and the optimal decision variables have been determined. From this aspect, the bullwhip effect is used as the supplementary indicator to evaluate system performance associated with different policies in this study. Experiments show that the manufacturing bullwhip effect can be reduced in the DUAL policy, and the remanufacturing bullwhip can be reduced in the shifted PULL policy. However, it is still hard to find a single policy which provides better results in both processes.

Besides the performance, we should note that there are various difficulties in implementing the above policies. The two control variables in DUAL policy can be readily solved, and this policy can be applied in practice relatively easily, whereas with the shifted PULL policy, solving the six optimal decision variables can be tedious work, and implementing this policy also requires auditing and checking information in several dimensions.

Owing to the difficulties in searching for optimal decision variables, this study has to limit the size of the simulation experiment. In order to have an extensive comparison of different policies and confirm the findings in this study, developing heuristics with a high solution quality will become an important direction for future research. Effort should be made to build simple formulae to obtain near-optimal values for the decision variables in the above-mentioned control policies such as Shift PULL, Separated PULL and DUAL. Not until then can we conduct a more comprehensive study of the bullwhip using approaches such as DOE analysis. The results will be of great interest in understanding and managing hybrid production systems.

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